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Patterns of current-induced transport in the surface layer of the Gulf of Finland

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The Lagrangian trajectory model TRACMASS based on an Eulerian field of velocities (calculated using the Rossby Centre Ocean Model), combined with relevant statistical analysis, is used for the identification of transport patterns in the surface layer of the Gulf of Finland from 1987–1991. The analysis of velocity fields and properties of net and bulk transport (the distance between the start and end positions of a trajectory, and the total length of the trajectory, respectively) shows the presence of semi-persistent (with a typical lifetime from a week to a few months) features of the surface-layer dynamics, a part of which evidently cannot be extracted directly from the velocity fields. The modelled surface dynamics mostly hosts an Ekman-type drift and, in yearly average, contains an anticyclonic gyre occupying the western part of the gulf. The prevailing transport directions to the east and slightly to the south match the direction of the Ekman surface drift created by predominant south-western winds. The spatial patterns of the net transport substantially vary over different seasons. The most intense net transport along the coasts occurs in the western and central parts of the gulf but contains relatively intense largely meridional transport pathways in some seasons.

Introduction

The movement of the marine surface layer and the accompanying drift of adverse impacts (e.g. oil spills, lost containers, or ships that cannot be steered anymore) in this layer are jointly governed by three factors: currents, wind and waves (Vandenbulcke *et al*. 2009). The transport induced by the latter two in semi-enclosed basins mostly (albeit not perfectly) mimics the behaviour of the wind patterns. The situation for the current-induced transport is fundamentally different. The instantaneous field of currents is an integral reaction of water masses to a variety of forcing factors mostly distributed over large sea areas but partially concentrated in river mouths. It is a highly nontrivial, anisotropic, inhomogeneous, non-stationary system with large spatial variation, even for practically stationary wind events. In semi-enclosed sea areas such as the Baltic Sea this system is frequently even in antiphase with wave- and wind-induced transport features (e.g. Andrejev *et al*. 2004a, Gästgifvars *et al*. 2006). For the above-mentioned reasons, drift prediction remains a very challenging task and even small errors in its estimates can drastically change the calculated particle trajectories (Griffa *et al*. 2004).

Marine science has only recently reached the situation where the development of mathematical models, the accuracy and reliability of circulation modelling, the computational facilities and the quality of information about forcing factors allow addressing the problem of drift prediction in a dependable way. Even though most of the contributions to such drift can be forecast by deterministic models to some extent, there is not yet a deterministic method to combine them in order to reproduce the floating object drift (Vandenbulcke *et al*. 2009). In particular, the inadequate representation of current patterns is one of the main reasons why the forecast of current-induced transport is much less reliable as compared with the description of wind- and wave-induced transport.

There are several ways to reduce the uncertainties in the current-induced drift patterns by means of statistical approaches such as the use of multiple runs of the same model or the use of model (super-)ensembles (Vandenbulcke *et al*. 2009). We focus here on a complementary technique to help lowering environmental risks in a marine environment, based on the optional presence of (statistically) semi-persistent current patterns. Such patterns, with a typical lifetime from a few weeks up to a few months have been recently identified for different areas of the Baltic Sea (Lehmann *et al*. 2002, Andrejev *et al*. 2004b, Meier 2007, Osinski and Piechura 2009). The existence of such patterns eventually has a high potential for the rapid and systematic transport of both water masses and adverse impacts such as nutrients, toxic substances, or oil pollution between specific sea areas. Their smart use can become one feasible way towards a reduction of anthropogenic impacts to vulnerable areas by placing human activities (such as marine traffic) in specific regions (areas of reduced risk), from which the transport of pollution to vulnerable or high-cost areas is unlikely (Soomere and Quak 2007).

When transporting dangerous goods on land by truck, there is typically an intricate system of permissions one has to obtain, following all sorts of regulations specifying when and especially on which route the transport has to be carried out to minimize risks in case of an accident. For marine transport rationales how to impose traffic routes to reduce environmental risks, for example of an oil spill reaching a vulnerable coastline, hardly exist at all. The Gulf of Finland is an area with extremely heavy ship traffic and thus a high risk of environmental damage caused by accidents. Consequently a careful investigation of drift patterns in this area can serve as a prime test case to develop an approach how to impose specific travel routes that minimize the risks to the coastlines. This does not mean to produce yet another operational model to assist rescue teams after an accident has happened but rather to identify beforehand regions where it is statistically safer to travel, by maximizing, for example, the time before a potential spill hits vulnerable coast, and thus reducing the impact.

Systematic identification of such areas generally presumes inverse tracking of the pollution propagation. A straightforward solution to this problem is not possible and no universal solution method exists. A feasible way to tackle it is to address the inverse problem with methods relying on the reanalysis of a large pool of numerically simulated transport patterns. Doing so eventually allows identifying the presence and basic (statistical) features of useful semi-persistent current patterns that may be used later for practical purposes.

Following this line of thinking, we focus on the analysis of the results of long-term, high-resolution simulations of the Baltic Sea circulation, with an emphasis on the Gulf of Finland. The main parameters of the models and the TRACMASS method, used for the extraction of information from the three-dimensional (3D) fields of currents, are described next, followed by discussion of the key properties of the current fields such as the average speed and long-term average Eulerian flow patterns. Finally, we analyse first results for semi-persistent Lagrangian transport patterns in the surface layer and certain implicitly obtained characteristics of the circulation such as an estimate for the typical size of the largest eddies, which implicitly characterize the ability of the model in use to represent the basic structure of currents in the area in question.

Circulation and trajectory models

The analysis below is mostly based upon a large ensemble of Lagrangian transport paths of water (and pollution) particles in a marine environment, for which velocity fields have been calculated based on the Eulerian approach. This study employs 3D current velocity calculated using the Rossby Centre Ocean circulation model (RCO) for the entire Baltic Sea. The horizontal resolution of the model grid is 2×2 nautical miles and the model uses 41 vertical levels in z-coordinates (Meier *et al*. 2003, Meier 2007). The thickness of the vertical layers varies between 3 m close to the surface and 12 m in 250 m depth. The uppermost layer, used in the analysis below, corresponds to water masses at depths 0–3 m. A time step splitting scheme is used in the RCO, with the choice of 150 s for the baroclinic and 15 s for the barotropic timestep. The output is stored once in six hours.

The RCO is a Bryan-Cox-Semtner primitive equation circulation model following Webb *et al*. (1997) with a free surface (Killworth *et al*. 1991) and open boundary conditions (Stevens 1991) in the northern Kattegat. It is coupled to a Hibler-type sea ice model (Hibler 1979) with elastic-viscous-plastic rheology (Hunke and Dukowicz 1997). Subgrid-scale mixing is parameterized using a turbulence closure scheme of the k-ε type with flux boundary conditions to include the effect of a turbulence-enhanced layer due to breaking surface gravity waves (Meier 2001). A flux-corrected, monotonicity-preserving transport (FCT) scheme following Gerdes *et al*. (1991) is embedded. No explicit horizontal diffusion is applied.

The model is forced with 10 m wind, 2 m air temperature, 2 m specific humidity, precipitation, total cloudiness and sea level pressure fields from a regionalization of the ERA-40 re-analysis over Europe using a regional atmosphere model with a horizontal resolution of 25 km during 1961–2007 (Samuelsson *et al*. 2011). The atmospheric forcing fields are extended beyond the ERA-40 period with analysis data from the operational ECMWF model (Anderson *et al*. 2006). As the atmospheric model tends to underestimate wind speed extremes, the wind is adjusted using simulated gustiness to improve the wind statistics (Samuelsson *et al*. 2011). Standard bulk formulae are used to calculate the air-sea fluxes over open water and over sea ice. For further details of the model set-up and an extensive validation of model output the reader is referred to (Meier 2001, Meier *et al*. 2003, Meier 2007).

From the variety of outputs of the RCO model, we only consider the velocity fields. The trajectories over different time intervals are computed with the TRACMASS model (Blanke and Raynard 1997, Döös 1995, de Vries and Döös 2001) from the RCO velocity fields off-line, i.e. after the circulation model has been integrated and the velocity fields have been stored. This approach has been applied to many different circulation models both for the ocean and the atmosphere (Fig. 1).

The trajectories are calculated based on a linear interpolation of the velocity field in each point of a particular grid cell with an adjustable temporal resolution that can be made basically equivalent to that of the RCO model. First the source point where the pollution may have been started (the initial position and depth of the trajectories) and the starting and ending time of propagation are specified. As we are specifically interested in what happens over several days, the coordinates of the instantaneous trajectory points are saved once in six hours. Doing so does not affect calculated statistics although it may cause some side-effects such as trajectories seemingly crossing some peninsula or islands (Fig. 2).

The resulting trajectories evidently will depend to some extent on the time interval of saving the circulation data and on the temporal resolution of the trajectory calculation scheme. In extreme cases, the resulting differences may lead to extremely large divergence of initially close trajectories. The experience with the TRACMASS code, however, reveals that the spreading of the calculated trajectories is normally much smaller than spreading of real drifters owing to the effect of sub-grid turbulence (Jönsson *et al*. 2004, Engqvist *et al*. 2006, Döös and Engqvist 2007, Döös *et al*. 2008). In other words, initially close trajectories have an overly tendency to stay close. This stability implicitly suggests that the potential impact of the time step of saving the circulation data or the similar effect of the choice of the temporal resolution

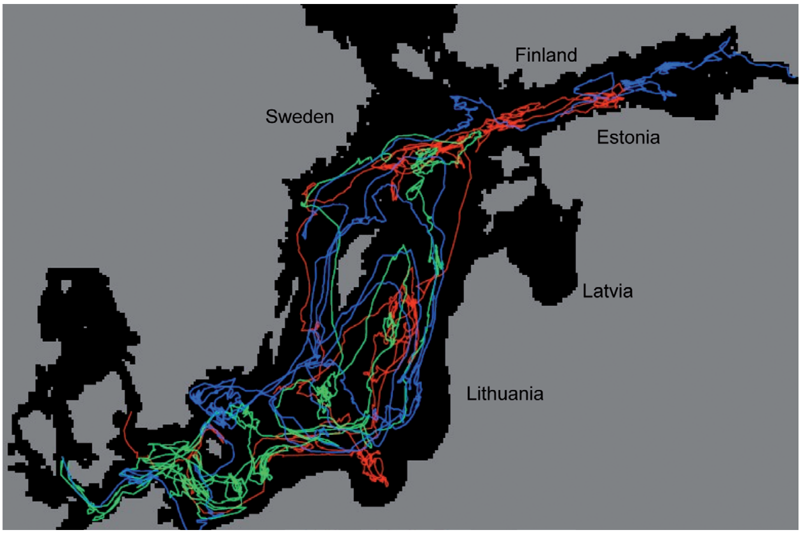

Fig. 1. The complexity of trajectories of water particles calculated using the TRACMASS code and the RCO model data in the Baltic Sea entering the sea through Öresund (red), Great Belt (green) and from River Neva through the Gulf of Finland (blue).

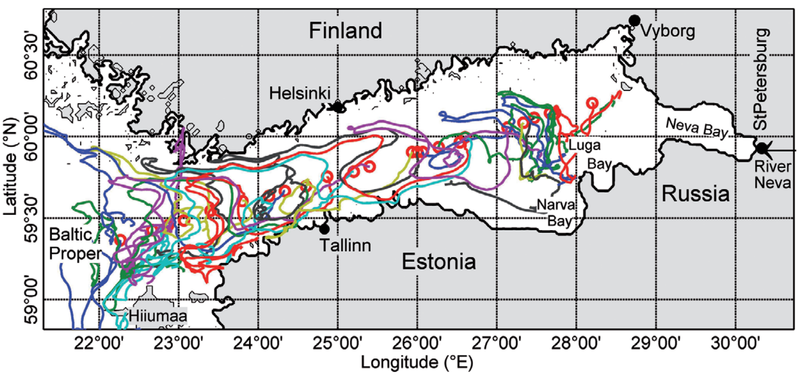

Fig. 2. The complexity of trajectories of water particles over 60 days calculated using the TRACMASS code and the RCO model data in the Gulf of Finland for 1987. Red circles show the starting points of the trajectories. The colours for trajectories are only used for distinguishing trajectories starting from different points.

in trajectory reconstruction is minor in terms of statistics of a large number of trajectories.

Properties of currents

The overall character of the average current field and its persistency are well known for the Gulf of Finland. A traditional but idealized view of the mean circulation of this basin, identified nearly a century ago, is that it is cyclonic with an average speed of a few cm s^{-1} (*see* Alenius *et al*. 1998, Soomere *et al*. 2008 and references therein). These features have been adequately reproduced in numerical models (for example, Lehmann *et al*. 2002) that have also indicated several non-trivial specific properties of the flow, such as the presence of numerous meso-scale eddies, the high persistency of the outflow in a subsurface layer and the predominance of the Ekman surface transport to the south-east (Andrejev *et al*. 2004a, 2004b).

For this study, using the current fields and large pools of trajectories calculated with the TRACMASS code, several parameters such as the average Eulerian velocities and circulation scheme, maps of the spatial distributions of Lagrangian net and bulk transport, and ratio of these two were estimated. The net transport is defined here as the distance between the start and end positions of a trajectory and the bulk transport reflects the total length of the trajectory. The analysis of trajectories allows the identification and visualization of several properties of surface currents that cannot be extracted directly from the current fields. Comparison of the average net transport calculated over certain time windows t_w with the average velocity fields allows, for example, identifying the areas that frequently host strong flow (the high values of velocity which frequently persist over time intervals $\geq t_w$) even if the flow direction varies over longer time intervals.

Earlier attempts to identify semi-persistent current patterns in the Gulf of Finland have indicated their clear presence in the subsurface layer (depths 2.5–7.5 m, Andrejev *et al*. 2004a, 2004b). The persistence of currents in the uppermost layer, defined in terms of the conservation of the direction of the flow over five years, was found to be very small. This, however, does not exclude the existence of semi-persistent transport pathways in which the velocity vector undergoes variations of its direction (for example, coastal currents with alternating directions).

As the uppermost layer is usually responsible for the most intense transport of various substances and also possesses the largest velocities of the water column, the identification of such surface patterns has the largest practical importance. For this reason the calculations for this study were made for the surface layer covering depths of 0–3 m in the Gulf of Finland and the adjacent area of the northern Baltic Proper (Fig. 2) for the period of 1987–1991. The choice of this time window and the surface layer allows matching the outcome with similar results of the earlier high-resolution simulations of dynamics of the Gulf of Finland for the upper surface layer covering depths 0–2.5 m (Andrejev *et al*. 2004a, 2004b).

The overall purely kinematic properties of the current field such as long-term transport speed (defined as the length of the average velocity vector for each point) of 0.01–0.07 m s^{-1} (Fig. 3) match well both the measured and earlier numerically simulated average values (Alenius *et al*. 1998, Andrejev *et al*. 2004a, 2004b). The average speed of water particles for the five-year period of 1987–1991 is 0.071 m s^{-1}. In order to account for the seasonality of the Baltic Sea dynamics, we divided the year into the following intervals: the calm period (May–August), the transition period from calm to windy (August–October), the windy period (October–March) and the transition period from windy to calm (March–May) (Räämet and Soomere, 2010). The highest speeds occur in the windy season when the average speed ranges from 0.074 to 0.097 m s^{-1} (Table 1). In the calm season the average speeds are much smaller (usually 0.03–0.05 m s^{-1}) but in some years may reach 0.08 m s^{-1}.

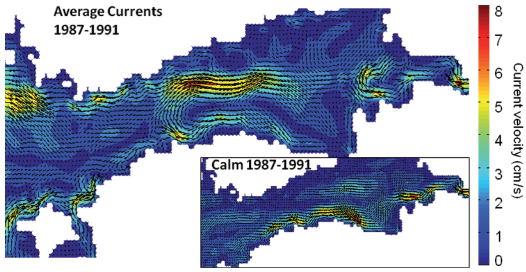

Fig. 3. Average velocity field over the entire period of 1987–1991 and during calm seasons (May–August, inserted panel) over the same interval in the Gulf of Finland. Both colour code and lengths of vectors show current velocity (cm s^{-1}).

The circulation patterns averaged over the years 1987–1991 (Fig. 3) show that the flow in the surface layer of the Gulf of Finland has a limited similarity with the classical cyclonic circulation scheme of water masses in this basin. There is, on average, a relatively intense inflow at both the northern and southern coasts at the entrance to the Gulf of Finland (Fig. 3). Their presence (separated by an area with almost vanishing east-west velocity) is well known from simulations with different models (Andrejev *et al*. 2004a).

Table 1. Average transport speed and average speed of water particles (m s^{-1}) over the entire surface layer in the Gulf of Finland for calendar years and for the windy season (October–March of the subsequent year).

		1987	1988	1989	1990	1991
Transport speed	Annual mean	0.018	0.024	0.028	0.030	0.024
	Windy season	0.035	0.056	0.041	0.027	0.042
Average speed	Annual mean	0.056	0.074	0.075	0.080	0.068
	Windy season	0.074	0.097	0.082	0.080	0.084

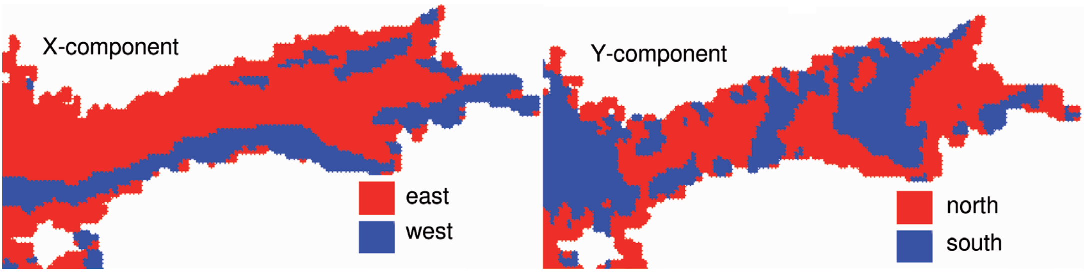

Fig. 4. The predominant directions of the *x*- and *y*-components for circulation of the Gulf of Finland for 1987–1991.

Differently from the results of earlier studies, in the 5-year average velocity field a large elongated in the east-west direction *anticyclonic* gyre covers a large part of the central area of the gulf. The inflowing current at the northern coast deviates from the coastal area after passing the narrowest part of the gulf and merges with the northern branch of this cell. The resulting wide band of relatively intense flow to the west continues until Narva Bay. The southern branch of this gyre is a narrow band of eastward coastal current along the Estonian coast.

This circulation pattern, albeit intriguing in the Gulf of Finland conditions, is not unique in water bodies of similar size and similarly (obliquely) oriented with respect to predominant winds such as the Great Lakes. While large-scale circulation patterns in the Great Lakes tend to be more cyclonic when the thermocline deepens and density effects become more important, an anticyclonic gyre was identified, for example, in Lake Michigan, sometimes occupying the entire southern basin of this lake (Beletsky *et al*. 2006). This pattern apparently dominates when the upper mixed layer is very thin. It is somewhat surprising and interesting that it becomes a dominant feature in the Gulf of Finland for 1987–1991. It is also important to notice that this gyre only becomes evident when the velocity field is averaged over a very long time and thus not necessarily reflects transport patters over a few weeks or months as discussed below.

The average of the *x*-component of the surface current field is directed to the east in most of the gulf (Fig. 4). The eastward current dominates, on average, in almost the entire northern part of the gulf (except for some small areas in the widest part of the gulf), whereas the current is directed to the west only in a narrow band at the southern coast. As a result, an overall domination of transport to the east is likely as suggested by Andrejev *et al*. (2004a, 2004b). For the interior of the gulf (eastwards from the latitude 24°E), its average speed over 1987–1991 is 0.0078 m s^{-1}.

The comparison of this spatial pattern of surface currents with the above-discussed overall features of the Gulf of Finland dynamics suggests that the motions in the surface layer are, in average, largely decoupled from the dynamics of the underlying water masses in the sense that the long-term circulation patterns in the surface and subsurface layer are quite different. Although the vertical velocity shear may be quite limited for most of time, its regular presence may give rise to strong vertical velocity gradients between the average motions in the uppermost and the subsurface layer. Such a jump in velocity is clearly visible from the results of earlier numerical simulations (for example, Andrejev *et al*. 2004a: fig. 12).

The described decoupling is evidently caused by the impact of predominant moderate and strong winds from the south-west (Soomere and Keevallik 2001, 2003). These winds create Ekman transport to the (south-)east and also force the nearshore surface current to the east near the Finnish coast. The resulting transport is directed oppositely to the overall cyclonic circulation in the northern part of the gulf. The water masses forced to move to the east subsequently cause the counter-flow along the southern coast of the Gulf of Finland. As the majority of the surface flow appears to be directed towards an eastwardly direction, a compensating flow should exist either in the subsurface or in deeper layers (Andrejev *et al*. 2004a, 2004b).

The described feature is possibly connected with the phenomenon of the intense pumping

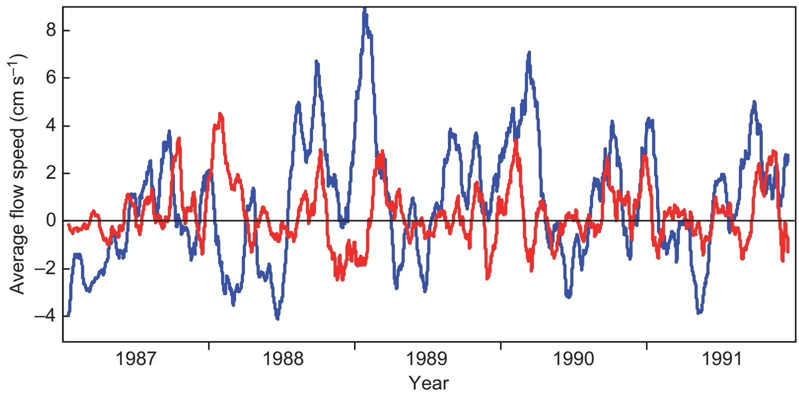

Fig. 5. Time series of the running average over 30 days of velocity components (blue: east–west component, positive to the east; red: north–south component, positive to the north) averaged over all sea grid points of the interior of the Gulf of Finland (eastwards from the latitude 24°E).

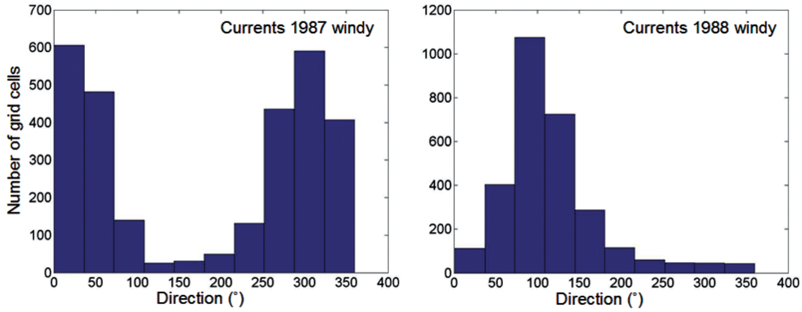

Fig. 6. The distribution of orientations of the average velocity vectors over the windy season in 1987 and 1988 in the sea grid points in the Gulf of Finland. Directions are counted clockwise from the north.

of water into the Gulf of Finland during strong westerly winds that may lead to the export of large volumes of saltier waters in the deeper layers of the gulf and to an almost entire loss of stratification at the gulf entrance (Elken *et al*. 2003). It is well known that the standard estuarine circulation could be reversed by appropriate winds, causing landward flow in the surface layer and seaward flow in the lower layer (Alvarez-Salgado *et al*. 2000, Gibbs *et al*. 2000). Whereas the standard circulation apparently exists for most of the wind directions in the Gulf of Finland, long-lasting, strong (south-)western winds may push a large amount of fresher surface water into the gulf. The excess volume of water increases the hydrostatic pressure in the gulf and may lead to a gradual export of the salt wedge in the bottom layer of the gulf (Elken *et al*. 2006). A reversal may occur if south-westerly wind speeds exceed as low a threshold for the mean wind speed as 4–5.5 m s^{-1} (Elken *et al*. 2003).

The spatial pattern of the average of the north-south component of the surface currents (Fig. 4) shows a predominant direction to the south at the entrance to the gulf and at the longitudes of Narva Bay where the average flow has clear similarity with the one calculated by (Andrejev *et al*. 2004a). A key consequence of this property is that, on average, the north-western coast of Estonia and the coasts of Narva Bay apparently are more frequently hit by adverse impacts transported by surface currents than other sections of the southern coast of the gulf.

An important feature is the large interannual variation of the prevailing transport direction within particular seasons. The typical monthly mean values of the average meridional flow component are generally of the same magnitude as the east–west component but show much more pronounced variability. The flow is, in average, usually to the south in windy seasons with relatively intense currents such as 1988/89 or 1989/1990, whereas in seasons with low currents (such as 1987 or 1990–1991, Table 1) the motion is directed to the north (Figs. 5 and 6). Although the overall average meridional flow component in the interior of the gulf is to the north, the average speed of this flow is very small, only 0.0026 m s^{-1}, and the simulations in

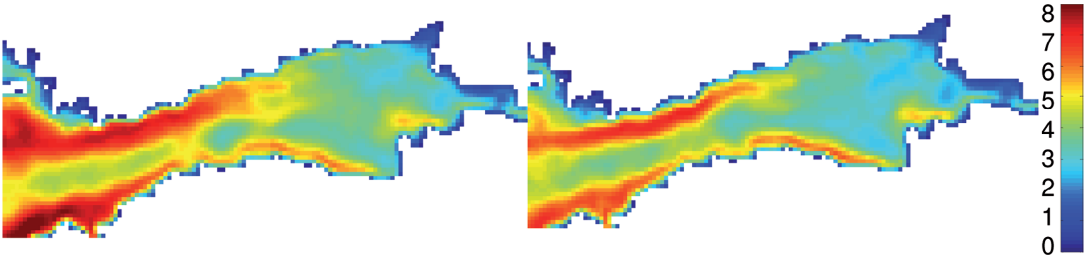

Fig. 7. Average net transport speed (cm s^{-1}) for 1987–1991 (left-hand side panel) and for 1987 (right-hand side panel).

question, thus, reveal no predominant direction of the meridional water transport. A substantial additional contribution to the southwards-directed transport may stem from the property of south-western winds to turn somewhat more to the west in the interior of the Gulf of Finland (Savijärvi *et al*. 2005, Keevallik and Soomere 2010). This feature apparently is not resolved in the forcing fields of the RCO model.

Patterns of net and bulk transport

A straightforward extension of the measure of the overall persistency of the flow used in (Andrejev *et al*. 2004a, 2004b) towards identification of flow patterns that persist over certain intermediate time scales consists in using the above-discussed definition of the net transport over certain time windows t_w. The net transport and its velocity within each window were calculated as the distance between the start and end positions of the trajectories simulated by the TRACMASS code. The result characterises the flow persistency in terms of Lagrangian velocity during the time window. In the limiting case t_w = 5 years it is equivalent to the persistency of (Andrejev *et al*. 2004a) in a Lagrangian framework. By varying the length of the time window and shifting it over the circulation data is it possible to identify patterns persisting over different time intervals and existing, for example, in different seasons.

In this study we mostly use a time window of 4 days that accounts for the internal circulation of most of the synoptic-scale eddies in the Gulf of Finland (*see* the relevant discussion below) and is about one half of the typical time of hitting the coast for tracers released in the surface layer of this water body (Soomere *et al*. 2010). One tracer was inserted in the centre of each grid cell. The first calculation was launched at 00:00 on 01 January 1987 for t_w = 4 days and was repeated with the same position of the tracers but with a time lag of 6 hours, 12 hours, 18 hours, etc., until the end of 1991. The average net transport and its velocity for each sea point were then calculated as an average over the entire pool of the results for 4-day sections and over selected time intervals (for example, over different seasons).

The spatial patterns of the resulting maps of the net and bulk transport speed and their ratio represent the ability of the surface flow in the Gulf of Finland to transport potential adverse impacts over such 4-day sections. They first highlight the areas where the flow (in terms of Lagrangian transport) may be fast or slow on average. Elongated areas of fast net transport evidently indicate pathways of fast movements of water masses and associated tracers. The map for the average net transport speed for the entire 5-year period from 1987–1991 (Fig. 7) shows that the fastest moving net flow on the surface layer occurs as a wide inflow band near the northern coast at the entrance and in the entire western part of the Gulf of Finland. There is also a limited area of eastwards flow near the southern coast of the gulf. The only more or less persistent net flow to the west exists as a coastal current along the north-eastern coast of Estonia.

These results mirror to some extent the above-discussed average circulation pattern: a persistent inflow at the northern coast of the gulf that merges with the northern branch of a large anticyclonic gyre in the interior of the gulf. It is characteristic that the match of the average (Eul-

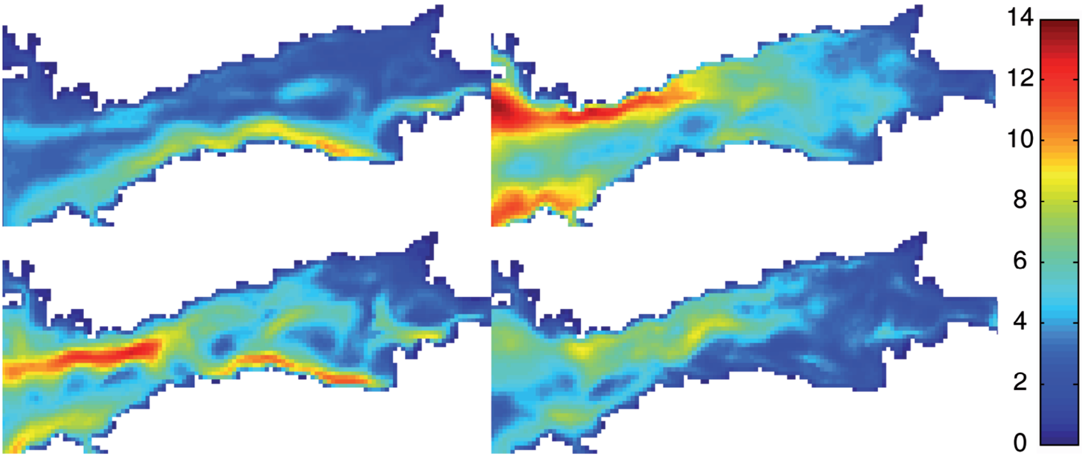

Fig. 8. Average net transport speed (cm s^{-1}) during the calm season of 1988 (upper left-hand side), windy period of 1988/1989 (upper right-hand side), windy to calm season of 1988 (lower left-hand side) and calm to windy season of 1989 (lower right-hand side).

erian) circulation and the intensity of (Lagrangian) net transport is only partial. For example, the maps of net transport speed indicate a clear band of inflow along the north-western coast of Estonia (Fig. 7), whereas this feature is very weak in the average current field (Fig. 3).

Differently from the above-discussed strong interannual variability of the average current patterns, the patterns for the average net transport speed are very similar to each other for all years in question. This feature suggests that the major pathways of fast Lagrangian transport are relatively stable although the patterns of Eulerian currents may vary. They all contain two bands of transport into the gulf in its western basin and characteristic areas of weak net transport in the very centre of the basin and in its easternmost part. A narrow band of westward transport near the southern coast of the gulf is only evident in selected years such as 1987 (Fig. 7).

An area of relatively intense net transport located to the west of the island of Hiiumaa apparently reflects the large-scale circulation of the northern Baltic Proper. It not necessarily enters the gulf but continues to the north from Hiiumaa and/or forms the famous semi-persistent front at the entrance to the gulf (Kononen *et al*. 1996).

The patterns of the average net transport speed for different seasons, especially for the windy and calm periods, are quite different. This feature may reflect the domination of subsurface currents over the impact of wind in low wind conditions as noted by (Gästgifvars *et al*. 2006). During calm seasons the band of intense net transport is usually located along the entire southern coast of the Gulf of Finland, whereas during windy seasons a similar band near the north-western coast is the most prominent. The transitional seasons frequently show combinations of fast transport bands near both north-western and south-eastern coasts of the gulf in spring, whereas relatively fast net transport is optionally observed also in the central area of the gulf during late summer and early autumn (Fig. 8).

The obvious differences in the spatial patterns of the largest average values for the Eulerian speed (Fig. 3) and for the net transport (Fig. 7) are the most pronounced in analogous patterns for the windy seasons, for which usually the most intense transport takes place.

A highly interesting feature of the net transport patterns is the presence of areas of relatively fast cross-gulf transport during a large number of transitional seasons (Fig. 9). The presence of such areas that are elongated in the meridional direction in both spring and autumn transitional seasons suggests that rapid pathways of meridional transport (that is, across the axis of the Gulf of Finland) of surface water masses frequently exist during these seasons. Comparison of such

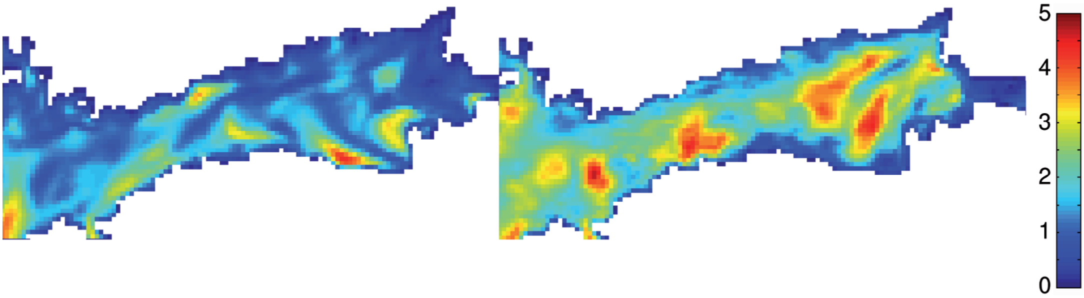

Fig. 9. The average *y*-component of net transport velocity (cm s^{-1}) for the windy to calm season of 1987 (left panel) and for calm to windy season of 1988 (right panel).

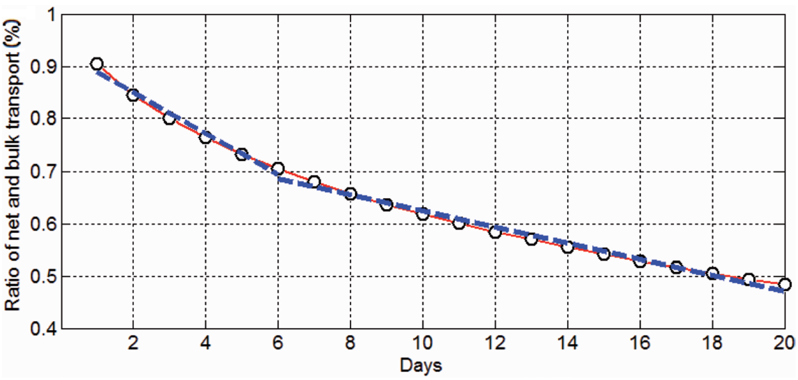

Fig. 10. Dependence of the average ratio of net to bulk transport on the length of the time window (days) for 1992 over the entire Gulf of Finland (3131 grid points, one tracer released into each grid centre; the calculations restarted after each 6 hours). Dashed lines show linear trends for days 1–5 and 6–30, respectively.

areas with the velocity data shows that the transport direction may be variable. For example, in 1987 it was mostly to the north whilst in 1988 it was to the south. The typical speed of net transport in such pathways is typically less than a half of the similar speed for meridional transport and reaches up to 0.05 m s^{-1}.

Such areas of relatively intense cross-basin transport evidently mirror the presence of certain well-known meso-scale features. The elongated areas that are largely aligned with the axis of the gulf may reflect regions where the coastal current usually separates from the coastal slope. Larger patches of intense north-south net transport may reflect either the position of frequent contact areas between slowly drifting meso-scale eddies or the typical positions of upwelling filaments.

The typical values of the net transport speed are close to average speed of water particles calculated componentwise over the entire Gulf of Finland and called transport speed (*see* Table 1). The average transport speed for the five-year period of 1987–1991 is 0.033 m s^{-1}, that is, about one half of the relevant average speed of water particles. The highest transport speeds occur, as expected, in the windy season when the average speed ranges from 0.027 to 0.056 m s^{-1} (Table 1). In the calm season the average transport speed is much smaller, usually 0.01–0.02 m s^{-1}.

The bulk transport was calculated as the total distance travelled by the water particle along the trajectory (that is, the length of the entire trajectory). The ratio of net to bulk transport in terms of distances is obviously close to 1 in the initial phase of propagation and decreases starting from the time instant when the trajectories start to bend (Fig. 10). Such bending may occur owing to a meandering of the currents, the presence of meso-scale (synoptic) vortices or inertial oscillations, etc. The temporal behaviour and the long-term limit of this quantity implicitly characterize the structure of the flow field. For example, for jet currents this quantity remains close to 1. It decreases infinitesimally for particles in the core of persistent eddies in a fixed location and tends to a certain limiting value for a field of gradually translating eddies.

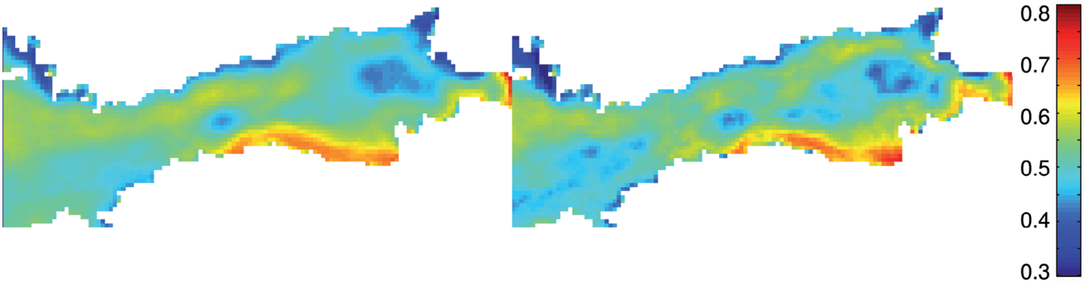

Fig. 11. Annual ratio of net to bulk transport for the five-year period of 1987–1991 (left-hand side panel) and for 1991 (right-hand side panel).

The analysis of this ratio allows to some extent to estimate the ability of the circulation model to reproduce the presence of meso-scale (synoptic-scale) eddies in the sea area in question and their impact on the structure of the surface transport. In sea areas where synoptic eddies play a minor role the average ratio of net/bulk transport is expected to decrease gradually at a slow pace. Although there are only a few direct measurements of such eddies in the Gulf of Finland (Soomere *et al*. 2008), they are generally thought to have an important (albeit not decisive) role in the system of currents. In such situations the average ratio of net and bulk transport is expected to decrease rapidly at first, within a few days, reflecting eddy rotation. After a certain time, however, the translation of eddies would play a role, and the rate of attenuation of this ratio should become much smaller. The bending point of the relevant time dependence roughly indicates the typical turnover time of the predominant synoptic-scale.

A relatively large change in the slope of the decrease of the ratio in question occurs for about 3–5 days in the Gulf of Finland (Fig. 10), possibly indicating the turnover time of the larger eddies. The average speed of currents in the surface layer of the gulf is 0.071 m s^{-1}. The maximum speed in the eddy cores is usually much larger, roughly about twice as high as the average speed, say, about 0.15–0.20 m s^{-1}. The perimeter of the core of such frequently occurring relatively large synoptic eddies in the Gulf of Finland, therefore, is about 20–30 km and their radius (understood as the distance from their centres to the area with the largest velocities) is about 4–6 km. This estimate matches well the estimates of the baroclinic Rossby radius for different areas of this water body (2–5 km, Alenius *et al*. 2003). This feature allows the conclusion that the RCO model represents the basic features of meso-scale dynamics of the Gulf of Finland correctly in the sense that it resolves the dynamics of the most typical examples of mesoscale eddies.

The spatial distribution of the ratio of net and bulk transport allows in addition distinguishing the areas where the current may be unidirectional from regions where it may have rapidly changing direction. Such distributions were calculated similarly to the distributions of net transport speed but only in terms of the relevant distances. As the time scale in which the role of bulk transport is properly resolved is a few turnover times of the typical mesoscale eddies, in this analysis we use time windows with the length of t_w = 15 days. The average ratio in question has a value between 0 and 1 and serves as a measure of the variability of the current direction for each sea point: it is close to 1 when the current is unidirectional and close to zero for eddy-dominated dynamics. Therefore, this quantity is also similar to the measure of persistency used in (Andrejev *et al*. 2004a, 2004b) but allowing the identification of Lagrangian transport patterns that persist over the length of the time window. Differently from the net transport (that does characterise rapid pathways but may include substantial excursions of the flow owing to, for example, inertial oscillations or mesoscale dynamics), the ratio of the net to bulk transport additionally shows how straight the motions of the tracer are.

The five-year mean ratio (Fig. 11) has a qualitative distribution similar to that of the flow persistency in (Andrejev *et al*. 2004b). Apart

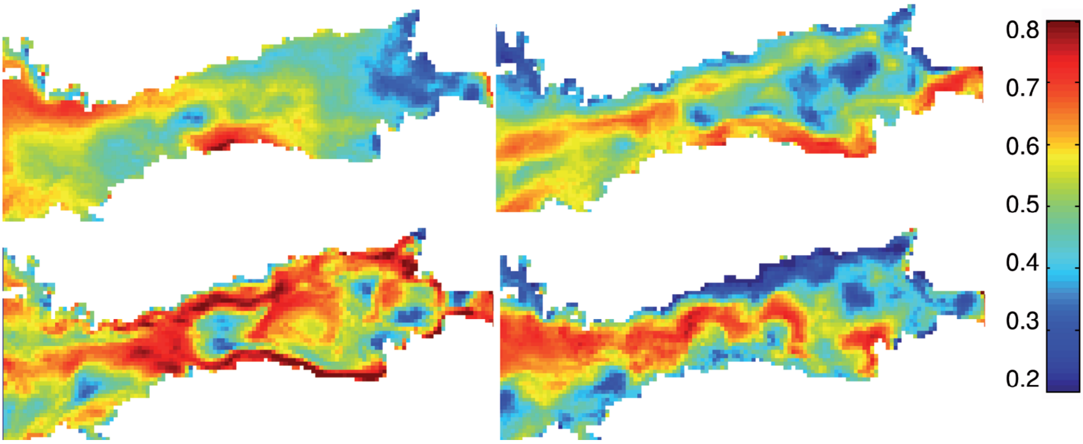

Fig. 12. Maps of the ratio of average net to bulk transport during the windy season of 1988/1989 (upper left-hand side), calm season in 1990 (upper right-hand side), windy to calm season in 1988 (lower left-hand side) and calm to windy season in 1989 (lower right-hand side).

from the obviously high values in Neva Bay evidently driven by the voluminous runoff of the River Neva, the map reveals two large bands of moderate and relatively high values of this ratio, more or less corresponding to areas with relatively high flow persistency. The largest values (in a range between 0.4 and 0.7) occur along the Estonian coast from Tallinn to Narva Bay. Somewhat smaller values, mostly below 0.5, occur in a wide band in the central and western Gulf of Finland slightly to the north from the axis of the gulf. The maps have features similar to the analogous distribution of the net transport (Fig. 6) but, for example, the area of rapid net transport at the southern coast of the entrance to the Gulf of Finland eventually contains a substantial amount of mesoscale oscillations.

The ratio in question shows, similarly to the net transport, very limited interannual variability in both the location of its maxima (Fig. 11) and the range of the largest values (0.7–0.8 for the area near the Estonian coast; about 0.6 near the Finnish coast in the western part of the gulf). Only in 1991 the area of relatively high values of the ratio (about 0.6) extends to Vyborg and Neva Bay along the northern coast of the gulf. The relatively poor similarity of maps in Fig. 11 with those of average velocities (Fig. 3) once more confirms that Lagrangian transport patterns not necessarily match the average of Eulerian currents.

Similarly to the net transport, the ratio of net and bulk transport exhibits substantial spatial variations during different seasons (Fig. 12). The maps of this ratio for windy and calm periods qualitatively resemble the similar map for the 5-year average of this quantity but show somewhat larger contrast of the underlying distributions. The area of high values in calm seasons (Fig. 12) matches the location of the area of overall high persistency of motions in the subsurface layer in (Andrejev *et al*. 2004a), suggesting that in low wind conditions the subsurface dynamics predominates also in the surface layer.

An interesting but also not completely unexpected feature is that small values occur for Neva Bay during windy seasons and large values during calm seasons. A somewhat surprising feature is the drastic interannual variation and the presence of rich internal structure of the area with maximum values of this ratio for different transitional seasons (Fig. 11). During these two-month sections several elongated across the gulf axis areas of high values of this quantity are evident in the central and eastern parts of the gulf. They may represent typical locations of long upwelling filaments or zones of large meridional velocities of basin-scale seasonal circulation patterns. Their nature, however, needs further research. It is also important to notice that there exists an extremely persistent area of low values of the ratio in question to the east of the Tallinn–Helsinki line.

Summary and discussion

The above analysis of the velocity fields and properties of transport created by the flow in the surface layer in the Gulf of Finland and a small adjacent section of the northern Baltic Proper has indicated the presence of several semi-persistent structures of the surface-layer dynamics in these water bodies, some of which evidently cannot be extracted from the straightforward analysis of the velocity fields. In order to visualize transport patterns and potential pathways, we have investigated the surface layer dynamics with the use of a pool of Lagrangian trajectories covering several years. The goal was to evaluate the basic parameters of current-driven transport such as the average net transport rate in different directions and the ratio of average net and bulk transport (equivalently, the ratio of the final displacement and the length of the trajectories). While several properties of the transport in question are intuitively obvious and/or can be consistently explained in terms of the existing knowledge, some features are counter-intuitive and further studies are necessary in order to understand their nature and role in the transport of adverse impact in the surface layer.

The model in use, although with a resolution somewhat lower than the one used in the most contemporary numerical simulations of the Gulf of Finland, reproduces well the basic features of the dynamics of the surface layer such as the average flow velocities, the spatial patterns of inflow and outflow through the entrance of the Gulf of Finland and the overall weak coupling of the surface dynamics with the flow in deeper layers (Lehmann *et al*. 2002, Andrejev *et al*. 2004a, 2004b). The prevailing direction to the east of the long-term average flow field in the Gulf of Finland suggests that extensive pumping of water into the gulf (and accompanying loss of stratification at its entrance) may happen quite frequently. An intriguing feature, not evident in earlier studies of the Gulf of Finland (but still noticed in similar studies into the Great Lakes circulation (Beletsky *et al*. 2006)) is the presence of a slow anticyclonic gyre in the relatively wide eastern part of the gulf.

The prevailing surface transport direction to the east and to the south over certain time intervals matches well the distribution of the frequency of upwellings in the Gulf of Finland (Myrberg and Andrejev 2003). It is intuitively clear that the relatively large probabilities of the occurrence of upwellings at the northern coast of the Gulf of Finland (compared with those for the southern coast) mean that strong Ekman transport frequently goes to the south-east. The consequences of this predominant transport direction and its role in the drift of oil spills or for search and rescue purposes, however, are not fully clear yet. It is obviously necessary to understand whether the described features are universal for the dynamics of the upper layer of the Gulf of Finland or whether are they partially caused by a specific resolution (and bathymetry), choice of atmospheric forcing, or by the scheme for resolving the vertical viscosity in the RCO model. The relevant analysis towards a comparison of the statistics of velocity fields and transport patterns with those obtained from the results of simulations by Andrejev *et al*. (2004a, 2004b) with a resolution of 1 mile and with an extension of their model to a resolution of 0.5 miles is currently in progress.

The spatial patterns of the net transport and the ratio of net and bulk transport show a very limited interannual but substantial seasonal variation. The large variability does not allow making definite conclusions about the possibilities of the forecast of the spatial distribution, persistency, relative strength or time scales of the formation of semi-persistent patterns with a lifetime between the typical time scale for mesoscale dynamics (a few days) and the length of a season (a few months).

Although the above has provided evidence about the existence of such patterns, the five-year period is definitely too short to create reliable statistics of their essential features or to establish their adequate correlation with the patterns of forcing factors. In particular, further analysis of such patterns evidently will make it possible to identify the areas where possibly mostly local eddy-driven circulation may exist and transport of adverse impacts to other sea areas is unlikely or very slow. These results will be particularly useful for identifying areas of low risk for the coasts.

An interesting feature is that in some seasons relatively intense mostly meridional transport pathways are present in the Gulf of Finland. Although they do not occur every year, their existence is of major importance with respect to the identification of areas of high risk in terms of coastal pollution. Their presence also suggests that between the typical turnover time of synoptic eddies (a week) and the length of a season (3–4 months) there may exist an intermediate time scale governing certain dynamical features.

In conclusion, the presented results of the use of a Lagrangian trajectory model based on Eulerian fields of velocities, combined with relevant statistical analysis, serve as a demonstration of the feasibility of this type of approach for the identification of semi-persistent transport patterns in the surface layer. The next step towards identification of areas of reduced risks consists in merging the detected patterns with the probability analysis of hitting vulnerable regions (such as the nearshore areas) by adverse impacts stemming from different sea areas.

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